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## INTERPRETATION OF ICE IMAGERY FROM ORIGINAL AND MODIFIED VERSIONS OF A REAL-APERTURE SLAR

by

Moira Dunbar



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ABSTRACT

SLAR ice imagery obtained with a Motorola AN/APS-94D and a Doppler beam-sharpened modification of it designed and built for the Department of National Defence by the Communications Research Centre is evaluated and the modes compared. The imagery was obtained in October 1976 in the Arctic Ocean and Nares Strait as part of Exercise BRISK. It is concluded that in its present form the DBS modification is less useful than the APS-94D for the extraction of ice information.

RÉSUMÉ

On évalue des images de glaces en mer obtenues à l'aide de deux radars latéraux aéroportés, le radar Motorola AN/APS-94D et sa version modifiée construite par le Centre de recherches sur les communications pour le compte du ministère de la Défense nationale. Les modifications apportées au radar Motorola consistaient à amincir le faisceau par un filtrage de fréquences Doppler. Les images ont été prises en octobre 1976 au-dessus de l'océan Arctique et du détroit de Nares pendant l'exercice BRISK.

L'étude montre que le radar APS-94D est plus apte que sa forme modifiée à produire des images pour l'analyse des caractéristiques de la glace.



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## INTRODUCTION

The imagery to be discussed in this paper was obtained by a Canadian Forces Argus aircraft as part of Exercise BRISK, a joint Canadian/UK exercise designed to obtain coordinated top and bottom ice profiles over a three-legged track in the Arctic Ocean (Figure 1, A B C D). Sonar and laser traces were obtained respectively by a nuclear submarine, HMS SOVEREIGN, and Argus 10728, which was based at Thule, Greenland, for the operation. The traces are being analysed at the Scott Polar Research Institute in Cambridge, England. In addition SLAR imagery of the entire flight track was obtained as well as infrared linescan of most of it.

The SLAR used was a Motorola AN/APS-94D which has been modified to operate in synthetic aperture and Doppler beam-sharpened modes by the Communications Research Centre in Ottawa under a Department of National Defence contract. It was used in the Doppler beam-sharpened (DBS) mode except on one flight, when it was restored to the original APS-94D format, thus providing an interesting opportunity for comparison.

## RADAR CHARACTERISTICS

The AN/APS-94D is a real aperture SLAR which images on either or both sides of the aircraft. The blank space in the middle represents a non-imaged strip having a width of about twice the flight altitude. The ranges used were 25 and 50 km a side, with corresponding scales of 1:250,000 and 1:500,000.

The range resolution of the APS-94D is fairly constant at about 30 m, but the azimuth resolution deteriorates across the range. At the flight altitudes discussed here it is approximately 40 m at 5 km from the track and deteriorates at the rate of 8 m per kilometre. The azimuth scale depends on ground speed, which is fed into the system and the scale automatically adjusted to approximate the range scale. Another automatic correction is made for aircraft drift, but heading changes can cause large distortions in the image geometry, since the aircraft track is always represented as a straight line.

This SLAR has been used by the author on many occasions (Dunbar 1975, 1975a; Dunbar and Weeks 1975).

The CRC/DND Experimental SLAR uses the APS-94D antenna and display sub-systems, but the rest of the system has been redesigned. It has been fully described in Barnes et al (1977). It generates a synthetic aperture interferogram which must be processed on the ground, and a Doppler beam-sharpened (DBS) video image which is recorded in flight in near real time in the same way as the APS-94D. The range resolution of the DBS mode is the same as for the APS-94D, but the azimuth resolution has been shown to be better by a factor of 4.5. The experimental SLAR can image on either side of the aircraft but not both at once, at ranges of 25 or 50 km as for the APS-94D.

### FLIGHT TRACKS

The aircraft made three flights, the first on 19 October to cover the first leg of the submarine track (Figure 1, A B) and the area of a planned rendezvous at  $84^{\circ}50N$ ,  $70^{\circ}00W$ , the second on 21 October to rendezvous with the surfaced submarine (Figure 1, B), and the third on 26 October to cover the second and third legs of the submarine track (Figure 1, B C D). This third flight had been planned for 23 October but had to be postponed owing to aircraft unserviceability.

In addition to the Arctic Ocean imagery, five traverses were made of Nares Strait, three of them straight down the middle and two, on 21 October, obliquely on a line between Thule and Alert\*.

This flight coverage resulted in a good deal of overlapping and repeated imagery in three areas: Nares Strait, the area around the rendezvous point, and between that point and Alert. It provided material for comparison between one mode and the other, and within each mode between different scales, altitudes, and look angles.

On all flights, the author acted as visual observer in the nose of the aircraft, recording observations by tape recorder. Although for much of the time cloud or darkness reduced visibility, a good deal of useful information was collected, and correlation between visual observations and imagery was good.

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\* For a map of Nares Strait see Figure 27.



### IMAGE QUALITY

In general the image quality was very good and quite consistent, and both modes produced many line-miles of good imagery. The following discussion pinpoints various aspects and comparisons that seem important and compares the DBS mode with the APS-94D as a vehicle for collecting ice information. It should be pointed out that the DBS mode is still in the experimental stage, and that in fact this was its first real operational test.

### ALTITUDE/RANGE PROBLEMS

#### DOWN-RANGE DETERIORATION

Flight altitudes varied from 915 to 3050 m (3000-10000 ft.), but the usual altitude when the laser was operating was 1220 m (4000 ft.), as this was considered to be the best compromise between the requirements of the various sensors. At this altitude and the 50 km range down-range deterioration, which is a SLAR characteristic and present to some extent in all the imagery, became fairly marked, but not always to the same degree. At 50 km and 1830 m (6000 ft.) noticeable down-range deterioration was experienced with the DBS mode but not with the APS-94D. However as only one sample of this altitude/range combination was obtained with each mode it would be unwise to draw conclusions.

One of the worst cases of down-range deterioration occurred on 19 October between the rendezvous point and Thule. Figure 2 shows smooth fast ice in eastern Kane Basin, with rough moving pack ice in the near range. Figure 3 shows the same area on 21 October, but from the opposite side (the arrows show flight track and direction). Both are in the DBS mode and at the 50 km range, but Figure 2 was flown at 1220 m and Figure 3 at 3050 m. Down-range deterioration is very marked in Figure 2, where floes B and C are barely visible, whereas floe A shows clearly in the far range of Figure 3. Admittedly A is a rougher floe than B or C and therefore a better target, but in Figure 3 there is little loss even in the smooth dark part of it. Floe D, however, in the extreme range of Figure 3, does lose detail. Serious deterioration may also be seen in Figures 8 and 25, which were taken shortly before Figure 2, and in Figure 11, this time in the APS-94D mode. Figure 9 is rather less bad and in this respect is typical of much of the imagery at this altitude-range combination. There is no obvious reason for this difference in degree of deterioration with range.

Down-range deterioration is caused by a low angle of incidence of the radar signal in the far range and is altitude dependent, as the lower the altitude the flatter will be the angle of incidence in the far range. Gray et al. (in press) discuss this question at some length in relation to AIDJEX imagery obtained with the same SLAR (APS-94D) and relate the onset of deterioration to incidence angles greater than  $75^{\circ}$  or  $80^{\circ}$ . These incidence angles occur surprisingly close to nadir, even at 3050 m flight altitude (see Figures 2 and 3) and they do indeed coincide with changes in tone values which are remarkably constant. Nevertheless very good imagery generally extends much farther down range. For practical purposes an arbitrary rule of thumb seems to emerge that with this SLAR the lowest flight altitude for optimum ice imagery at the 50 km range is about 1830 m (6000 ft.), which gives a maximum incidence angle of  $88.0^{\circ}$ . Acceptable imagery is possible at 50 km and 1220 m (4000 ft.) with a maximum angle of  $88.6^{\circ}$ , but this small difference in angle causes significantly greater down-range deterioration. At 3050 m and 50 km the maximum angle of incidence is  $86.5^{\circ}$ , accounting for the better far-range imagery noted in Figure 3, but at this altitude problems of signal strength sometimes arise. At the 25 km range very good results were obtained at 1220 m and also at 915 m (3000 ft.), which gives the same maximum incidence angle as the 50 km range at 1830 m ( $88.0^{\circ}$ ). On previous occasions good imagery has also been acquired, though not invariably, at 25 km and 610 m (2000 ft.), which is the same as 50 km at 1220 m (maximum angle of incidence  $88.6^{\circ}$ ) but unless other factors demand the lower altitude 900-1200 m is considered preferable when using the 25 km range.

There is another point that should be made before leaving the question of image quality in relation to altitude and range, and that refers to a quirk of this particular SLAR. Figures 6 and 7, for instance, show the north part of Kennedy Channel on 26 October. The edge of the fast ice on the west side of the channel shows up clearly in Figure 6 (915 m) but not in Figure 7 (1820 m). This difference might be attributed to flight altitude, since this is the only obvious variable; both images are at the same range (25 km) and imaged in the same mode (APS-94D). However there is another variable in that in Figure 6 the west coast is on the left side of the aircraft and in Figure 7 on the right. It is a peculiarity of this SLAR that, owing to a slight unevenness in the mounting of the antenna, it has a larger angle of incidence on the left than the right side at the same range. This tends to result in better imagery in the near and mid ranges on the left antenna, and although there is a corresponding tendency to greater deterioration in the far range at low altitude-to-range ratios, in general the left antenna produces better imagery. Thus, while flight altitude probably does contribute to the difference in clarity of the fast ice edge in Figures 6 and 7, the extent of its influence is hard to evaluate.

This factor has been allowed for in all comparisons, and all examples are taken on the same side of the aircraft unless otherwise noted.



### SCALE DIFFERENCE

Another aspect of the altitude-range question is that of preferred scale. There were several cases where imagery of the same area was obtained at different scales, one using the same mode (APS-94D), the other using different modes. No repeated coverage in the DBS mode at different scales was obtained.

Figures 4 and 5 show Kane Basin on 26 October, Figure 4 northbound, at 915 m and 25 km, and Figure 5 southbound, at 1830 ft. and 50 km. The ice is all moving pack except the smooth area on the east side, but the time interval (10 hours) is not great enough to alter the picture much, so that all the same floes remain in roughly the same relative positions. A detailed comparison reveals that, although the larger scale appears less cluttered, there is little difference in the features visible.

Figures 8 - 10 show an area north of Alert that was imaged on all three flights. Figures 8 and 9 are in the DBS mode at 50 km, Figure 10 in the APS-94D at 25 km. Apart from the changes in the ice itself between one flight and the next the chief difference is that there is a greater variety of grey tone in Figure 10. This, however, is due more to mode than scale difference (see p.10).

Figure 11 shows the area near the rendezvous point imaged by the APS-94D at 1220 m and 50 km on 26 October. It may be compared with Figures 12 to 14, showing the same area on 21 October in the DBS mode at 1220 m and 25 km. In this case the DBS image is at the larger scale, and the main difference is that in Figure 11 the ridges have a greater tendency to run together owing to inability to resolve them separately. This is partly due to the poorer resolution of the APS-94D, but the effect is emphasized by the scale difference.

From these examples it would appear that scale makes little difference to the amount of information contained in the image. However the larger scale provides a less crowded image, and if detail rather than area covered is required, or if a flight altitude below 1500 m (5000 ft.) is for some reason necessary, the 25 km scale is considered to be more satisfactory.

### NEAR-RANGE IMAGERY CHARACTERISTICS

The very near range is also sometimes subject to deterioration, which expresses itself in the form of a uniformly bright signal sometimes amounting to flare-out. Figure 9 is an example of this, though in this case

the flare-out is due to printing; it is not there in the original. With careful gain control flare-out is usually preventable, and the enhanced near-range image can sometimes prove an advantage, allowing small smooth features which normally tend to get lost to show up clearly. This effect can be seen in Figures 13 and 14, taken on 21 October at the rendezvous. Point A on Figure 14 shows a small smooth area with a narrow crack leading away from it. The same feature in Figure 13, while still dark, does not stand out from the rest of the floe, all of which is much darker than in Figure 14, and the crack, though it can be seen, is barely noticeable. In Figures 15 and 16 we have a slightly different case, where points A and B, which appear completely smooth in the very near range in Figure 15, reveal some roughness in Figure 16. The opposite however is true of Point C, where the texture visible in Figure 16 in the near range is resolved in Figure 15 into a single ridge. The reason for this is obscure. A more typical example of loss of detail in the near range may be seen between points A and B and on the other side of B, where Figure 16 contains much ridge information that is not in Figure 15, while Figure 15 differentiates better between leads and rough ice.

#### RELATION OF GREY-TONE TO ICE AGE

Gray et al (in press) point out that this tendency to stress the surface texture (grey tone) in the near range (up to 75 or 80° incidence angle) and topography (ridges) in the farther range is characteristic of the APS-94D imagery. They maintain further that in the near range the greater variation of grey tone differentiates multi-year (brighter) from first-year ice (less bright) as well as showing up the smooth refrozen leads, which are presumed to be young ice (dark), and that beyond about 80° incidence angle this tonal differentiation is lost. In the case of the AIDJEX imagery with which they were working, and which was well ground-truthed, both these statements seem to have been true, but the Nares Strait imagery suggests that it may be an oversimplification. Let us consider these points, using only the APS-94D imagery, as this was the mode used on AIDJEX.

First, can grey tone be equated to ice age in the near range? There is some evidence in the present imagery to support this theory. Figures 18 and 19 provide two examples, one definitely and the other possibly favourable to it. Floe A is a multi-year floe, as are almost all the discrete floes in Nares Strait at this time of year, and floe B appears to be either first-year or young ice, apparently formed in the quieter waters of eastern Kane Basin; it and the neighbouring floes have drifted northwestward in the nine hours between the images. In Figure 19 they are both in the very near range and the multi-year one is very much brighter, while in Figure 18 they are beyond the 80° line and the difference in grey tone between them has disappeared. On the other hand floes C to F, which have the appearance of first-year ice, have the same scattering characteristics as the multi-year floes even in the very near range. They thus do not fit the Gray model

if they are indeed first-year. However they may not be. Large first-year floes are very unusual in this channel, and these pieces can all be fitted together into a very large floe about 15 km long, which must have broken up quite recently. It is quite probable that it is actually rather smooth multi-year ice that looks like first-year because of the clean-cut recent breaks. Unfortunately visibility was restricted by cloud on the northbound trip and by darkness on the southbound, and although the aircraft flew right over two of the floes in daylight they were not clearly seen.

However, if this is a doubtful example, many examples can nevertheless be found in which first-year ice does not conform to the Gray pattern. Figure 17, for instance, shows part of Hudson Strait in the spring of 1975. Reconnaissance data from the previous fall show that there was no multi-year ice present. Yet, excluding the open or refrozen leads, the ice still shows a considerable variety of grey-tones which represent roughness and smoothness in the first-year ice. Figure 20 is an even better example because it is ground-truthed by several low-level flights in a Beaver aircraft, combined with landings at two points (X and Y). It shows Kennedy Channel on 13 March 1975, with a large patch of smooth first-year ice at the north end. The low-level flights were made in the third week in May, using the SLAR imagery as a map. The ice at X was 1.5 m thick and at Y 2.2 m. From NOAA IR imagery it appears that the smooth patch formed about mid January, which was the time the ice in the strait consolidated, so by mid March it must have been well into the first-year category, probably around a metre thick. The surface at X was as flat as a billiard table (Figure 21) becoming slightly rougher owing to rafting towards the coast of Ellesmere Island, and the bright features at A were very rough floes of (from the air) indeterminable age, possibly broken off from the fast ice. To the south of the smooth patch the identifiable separate floes were all multi-year and the matrix cementing them together all first-year, though probably with inclusions of some of the previous year's brash ice.

It is clear that here the multi-year floes conform pretty well to the Gray model, bright in the near range and losing their brightness down-range. However the scattering characteristics of the first-year ice are more complex. In the near range the smooth first-year ice can be separated from the multi-year floes by grey-tone, but the rough first-year ice surrounding the multi-year floes is often of equal brightness with the multi-year in the near range (B) and much brighter in the mid range (C). Thus there is no simple relationship here between ice of different ages at any range.

This brings us to the second point: Is gray-tone difference lost beyond an angle of incidence of  $80^{\circ}$ . This is certainly not the case in Figures 17 or 20. In the latter the smooth ice does show a darkening beyond  $80^{\circ}$ , but it is still different from the multi-year. The rough first-year ice



looks much the same at B and C. The roughness features towards the coasts in the smooth area, as for instance between X and Y, are not the result of better ridge discrimination (as against grey-tone) in the farther range, but reflect a real difference in the conditions. At Y the small dark patch, where the landing was made, was smooth, and (in May) largely bare, though it may have been snow-covered in March. The rest of the fast ice was extremely rough and contained a fair amount of multi-year ice (Figure 22)\*. The grey tones not only distinguish these two extremes and the river delta to the left of Y, but also some floes in the fast ice south of the delta which are apparently less rough than the surrounding ice.

Another type of ice that produces high scattering at all ranges is shuga - unconsolidated young ice made of many small pieces. Figure 23 (right side) shows this kind of ice in Smith Sound in January 1973. The brightest streaks are ice, the darker grey clutter is water. Note also the floe at A, which has just broken off from the fast ice and may be of any category from grey to first-year ice. Except for a bright line on the north side it appears slightly darker than the shuga, which has more facets (roughness) to return the radar signal. The left side of the image has smooth young floes and some water clutter, and here there is a definite falling off of contrast down-range, probably partly due to being on the right-hand antenna.

It is concluded therefore that, while there is clearly some justification for the findings of Gray et al, they would seem to be based on too uniform and restricted a sample. The whole picture is much more complex. Tonal discrimination is not necessarily lost, even in the far range, and it is not always possible to relate grey tone to age, even in the near range.

Difference in grey tone has been related by the present author (Dunbar 1975; 1975a) to surface roughness, and further experience with better ground truth has done nothing to alter the conviction that this is the dominant if not the only factor involved. Surface roughness is not necessarily related to ice age or "type", and ice of the same age does not necessarily have the same scattering characteristics at the same angle of incidence.

#### RIDGE DIRECTION

Figures 12, 13 and 14 represent three runs flown in a pattern round the position of the surfaced submarine. As such they present an opportunity to see the same area from different angles and to test the ability of the SLAR (DBS mode only) to pick up linear features at different angles. The imagery shows a surprisingly high degree of consistency in this and other ways. In particular Figures 12 and 13 are oriented almost at

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\* The term "fast ice" is used here to denote the ice inshore of the shear line, which was shore-fast before the rest of the channel consolidated. By March the whole channel was of course fast ice.



right angles and they are remarkably consistent in the delineation of ridge features. Floes B and C may be cited as examples, in which ridges show almost as clearly when perpendicular to the track as when parallel to it, and floe D has a ridge which shows up clearly in the farthest range of Figure 13 although it is almost exactly perpendicular to the flight direction.

### SMOOTH ICE AND WATER

The inability of X-band SLAR to differentiate between one smooth surface and another is one of its few real drawbacks as an ice reconnaissance tool, as the same return may represent open water or ice a metre or more thick. This was pointed out by Dunbar (1975) with the qualification that there are many cases in which the ice/water problem can nevertheless be resolved. If the surface is ice it very frequently displays lines caused by small linear features such as rafting or small ridges, and water, even in small areas among ice, can have a rippled surface which produces a characteristic clutter. A good example of this kind of indirect interpretation occurs in Figure 24. The streaks running up and down the channel at A and B are made up of small ice fragments lined up by wind and current, and this phenomenon, which is quite common, can occur only in otherwise open water (see also Figure 23). However there are many cases of completely nil return where uncertainty exists, and this is particularly true of the leads, usually relatively narrow, which develop in the Arctic Ocean, as they are often dead calm if open and without any surface feature if frozen. The leads imaged during this exercise are no exception, and in no case can we say for sure which contained open water, though in some cases indirect evidence or correlation with visual observations gives useful indications.

The large new leads in Figure 9, for instance, have developed in the two days since Figure 8, and there is a high probability that they are at least partly open. The imagery itself gives no clue except for some returns at A, which could be new ice or debris resulting from the break and floating in open water. The same leads in Figure 10, five days later, are at least partly refrozen, and we can discern different stages of freezing, progressing generally, as is normal, from the edges of the lead towards the middle. In some cases, where secondary movement has reopened the lead, the open, or more recently open, portion is not in the middle but on one side, or wanders from one side to the other. Whether these portions are water or thin ice it is not possible to say, though the visual notes mention open water or "open bits" at the arrows. The interesting point is that the image does distinguish two or more tones, so there must be a difference in surface roughness or some other relevant factor. It cannot be thickness as such, as there are many cases on record of completely refrozen leads, thick enough to have a dry snow cover and appear white to the visual observer, which present a nil return on the SLAR imagery.

Another example worth noting is shown in Figures 15 and 16. At C in Figure 16 there is some return from the middle of the lead but none at

the edges. This is a recurring pattern in lead representations in the DBS imagery, and in this case at least does not mean that the lead was open at the edges, as visual notes indicate that it was completely refrozen. The lead at A in Figure 15, according to the visual notes, probably contained some open cracks, but B is described as firmly frozen. In no case does the DBS imagery show the typical pattern of lead refreezing shown in Figure 10. It is suspected that this may be due to the lack of grey tone sensitivity of the DBS mode.

#### APS-94D VS DBS MODE

#### RESOLUTION AND GREY TONE

The spatial resolution of the DBS imagery, as has already been stated, is the same as that of the APS-94D in range and better by a factor of 4.5 in azimuth. The result is a much cleaner-looking picture which might be expected to contain much more information. When imaging some types of surface, particularly man-made objects, this may well be true, but for ice imagery a closer examination shows that in fact it is not the case, chiefly because the improvement in spatial resolution is accompanied by a decrease in grey-tone discrimination.

This factor has already been touched on in discussing the leads in Figures 8 - 10. This is however a poor example, since changes had occurred in the ice between flights. Figures 25 and 26 show an example in the fast ice in Newman Bay, taken on 19 and 26 October respectively, Figure 25 in the DBS mode, Figure 26 in the APS-94D. Both show Newman Bay on the left antenna but the altitude and scale are different. In comparing them we will use only the Newman Bay ice, as all the rest is pack ice and has changed completely in the seven days between flights. Land imagery should also be ignored, as Figure 25 suffers from the increased shadow effect of the lower altitude as well as down-range deterioration due to the combination of altitude and scale as discussed above.

A careful study of the Newman Bay fast ice reveals that the APS-94D imagery, though it is fuzzier, in fact contains all the information that is in the DBS, and that in addition it has a wider range of grey tone. Thus in Figure 26 the smooth ice at A and B is clearly of a different surface texture than the older floes (C) that have drifted into the bay during the open period, but in Figure 25 they all look the same. The same point is illustrated in Figures 2 and 5, which show Kane Basin on the same two flights, at the same altitudes as for Newman Bay but both now at the 50 km range. Again we discount the down-range part of Figure 2 and concentrate on floe A, which is about mid-range on both figures. The centre of this floe is made up of two sections, one darker (smoother) than the other. In Figure 2 the

smoother part appears exactly the same as the younger fast ice that surrounds the floe, but in Figure 5 it is represented by an intermediate grey tone. The same is true of floe D.

Associated with this lack of grey-tone sensitivity is a high degree of speckle in the DBS imagery. Looked at with a magnifier the imagery looks like a very grainy photograph. Ridges appear as rows of discrete spots and surface texture as a scatter of dots that is hard to relate to actual features and thus reduces the advantage of the improved resolution. Both these problems could be improved on by additional hardware to provide a multiple-look capability (Barnes, personal communication).

### IMAGE STABILITY

Another shortcoming of the DBS mode is its extreme sensitivity to aircraft motion, whether due to heading change or turbulence. The problem here is that the APS-94D antenna cannot be fully motion-compensated, so that aircraft movement introduces errors in the Doppler frequency. Much of the DBS imagery of Nares Strait was rendered useless by this factor. An example is Figure 24, which is marginal but usable; the imagery of Hall Basin and Robeson Channel from the same flight contains no usable information. The APS-94D is subject to the same sort of trouble (e.g. Figure 11) but is very much less sensitive. Of the total film footage over ice in the DBS mode, 15% was useless and 20% marginal, whereas of the APS-94D footage all was usable and only about 6% was substandard (not really marginal).

### COVERAGE

The present version of the DBS mode can image on only one side of the aircraft at a time. Actual experience of flying with both modes was that this reduction of coverage by half is a real drawback in ice reconnaissance. It is like flying with one blind eye and in particular reduces the possible correlation with visual observations, a factor that will be of the greatest importance in the operational use of SLAR for ice reconnaissance, particularly in the early stages. It is not, however, a necessary aspect of the system. To image both sides merely requires the addition of a second processor (Barnes, personal communication).



## SUMMARY

The APS-94D imagery proved superior in grey-tone sensitivity, coverage, and image stability. The DBS mode was better only in spatial resolution, which however did not result in a corresponding increase in the ice information obtainable from the imagery. Thus for ice reconnaissance purposes it must be concluded that, for the present at least, the APS-94D remains the better sensor. The DBS mode is, however, capable of further development and could be much improved.

## APPLICATION

The purpose of this report is to discuss the method rather than to apply it. However it may be of interest to point out some of the information that can be extracted from this imagery in addition to a record of ice conditions at a given time and place.

## ICE MOVEMENT

Repeated SLAR imagery is of course a useful way to record changes in ice conditions and measure ice drift, especially in areas where a coastal reference is available to facilitate direction and distance calculations. These conditions were present in Nares Strait, and the three flights spaced over a period of seven days gave a good opportunity for tracking floes. Changes in the ice in the Arctic Ocean were also recorded.

The development of the leads in Figures 8 - 10 and at the rendezvous point have already been discussed.

Far more spectacular is the Nares Strait imagery, in which at least a dozen individual floes can be tracked on two or more of the three dates the strait was covered, thus giving valuable information on drift rates.



Figure 27 shows the drift of five floes, designated S,T,U,X, and Z, from 19 to 26 October. Two of them (X and Z) appear on all three dates. The floes may be seen in Figure 25 on 19 October, Figure 24 (X and Z) on 21 October, and Figure 5 on 26 October. All except X are also in Figure 4. Overall drift speeds for the whole period vary from 0.28 m/sec (0.55 knots) for floe X to 0.65 m/sec (1.27 knots) for floe S. The fastest speeds were from 19 to 21 October: 0.62 m/sec (1.21 knots) for X, and 0.94 m/sec (1.85 knots) for Z.

### CONCLUSIONS

The overlapping and repeated imagery obtained on this exercise provided an excellent opportunity for studying the characteristics of these two SLARs as vehicles for ice information. The results on the whole confirmed the author's previous findings (Dunbar 1975), that SLAR differentiates roughness, not thickness (which is related to age) and that there is little or no direct relationship between grey tone and age/thickness category. Furthermore, as grey tone values change across the range, there is not even one single relationship between grey tone and roughness.

The work of Gray et al (in press) suggests that less subjective ways of interpretation will be found, but that more knowledge is required of the apparently complex relationship between the radar antenna and the ice before these can be worked out. In the meantime it could be very misleading to relate grey tone directly to ice age.

In comparing the APS-94D and DBS modes there is no doubt the APS-94D was the more satisfactory. However, it must be remembered that this was a first trial of the DBS mode. If the problems of grey tone discrimination and image stability can be overcome it will be a much improved tool, superior to the APS-94D in resolution and with the advantage over synthetic aperture radars of near real-time read-out. It thus could potentially be the best possible type of radar for ice reconnaissance.



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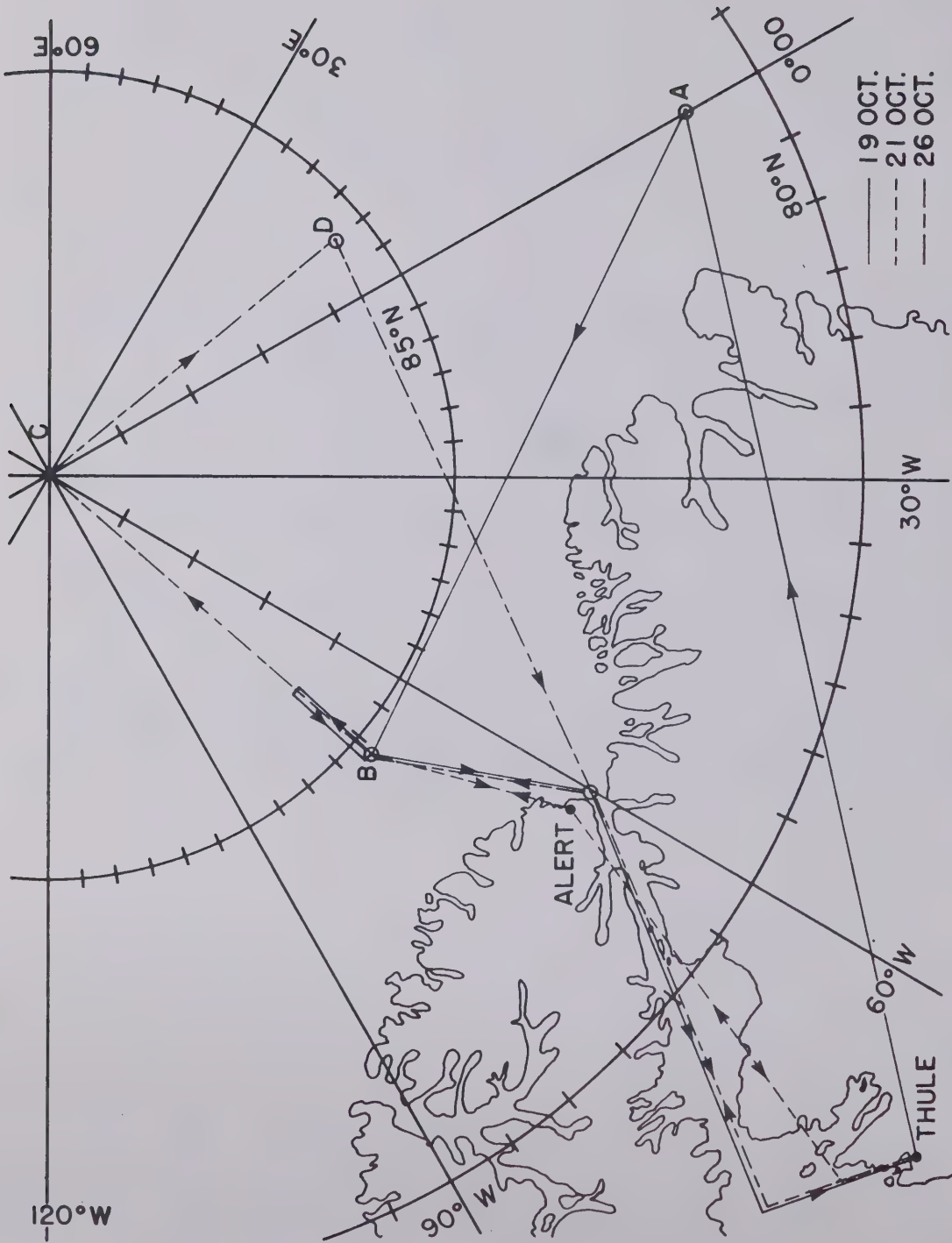


FIG. 1. Track chart. The letters ABCD indicate the track of the submarine.



FIG. 2. Kane Basin, 19 October. On the right is fast ice (dark), on the left moving pack ice (bright). The figures show the positions of the  $75^\circ$  and  $80^\circ$  angles of incidence. Altitude 1220 m (4000 ft) range 50 km, DBS mode (see p.3, 10).

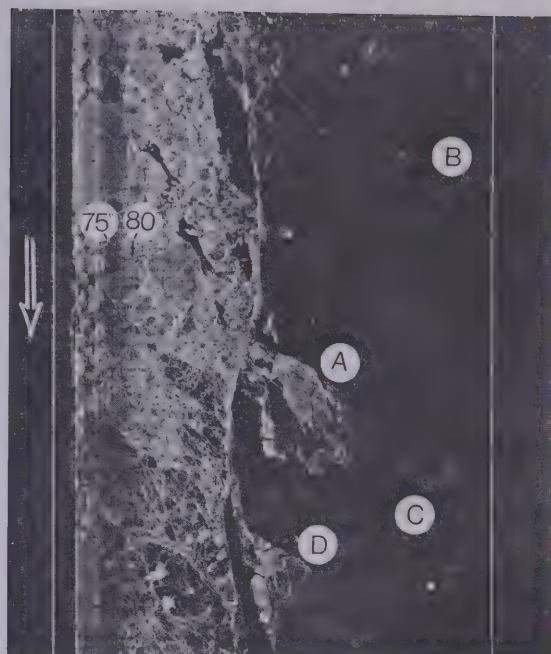


FIG. 3. The same area looking the opposite way, 21 October. Down-range deterioration is much less than in Fig. 2. The horizontal blank stripes are due to aircraft motion. Alt. 3050 m (10,000 ft), range 50 km, DBS mode (see p.3).



NOTE: All figures are oriented with the north (in Nares Strait northeast) at the top. Arrows show flight direction and, for DBS imagery, aircraft track, indicating look direction.

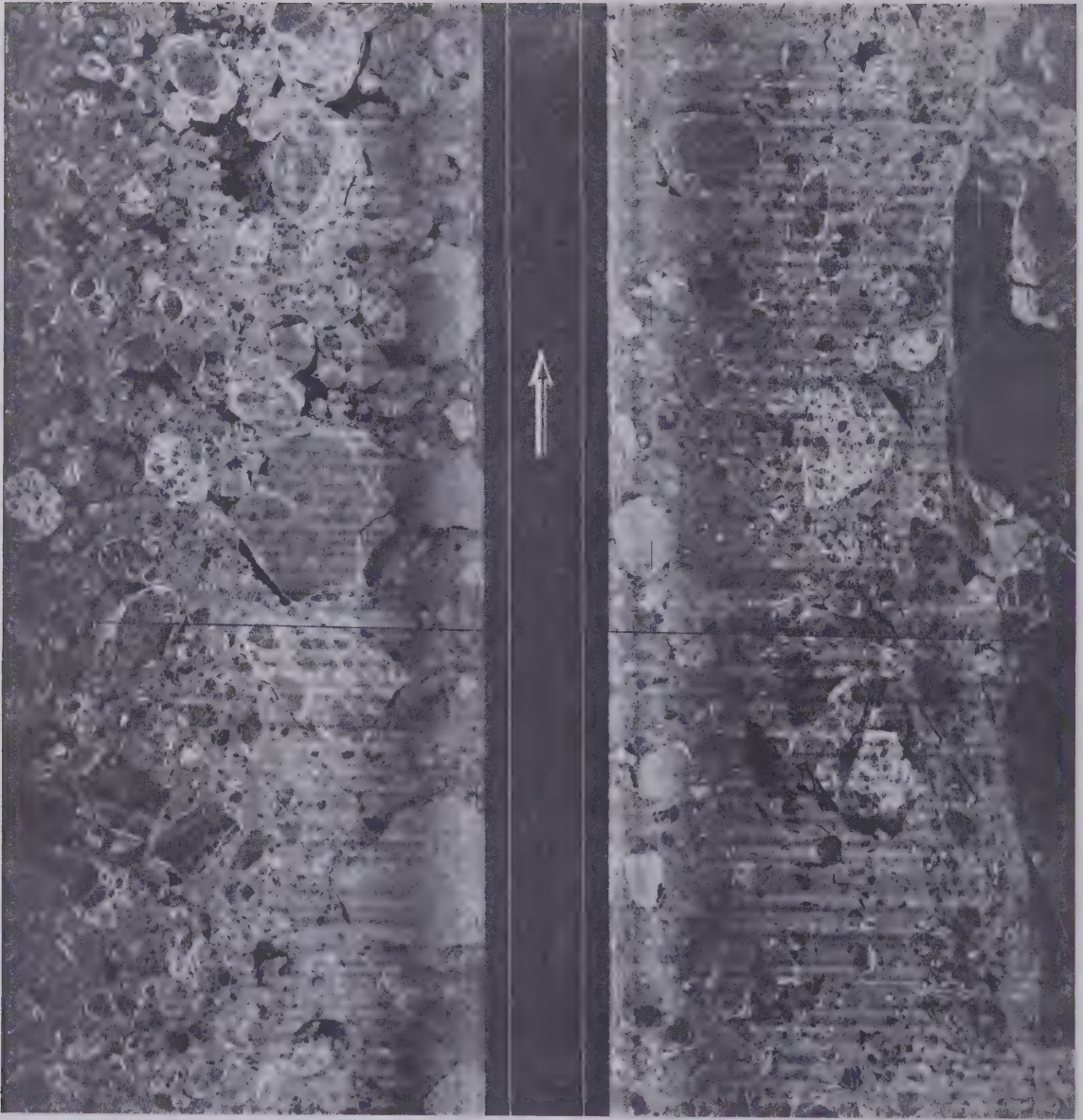


FIG. 4. Kane Basin, 26 October, on approximately the same track as Fig. 2 but northbound and looking both sides. Alt. 915 m (3000 ft), range 25 km, APS-94D mode (see p.5, 13).



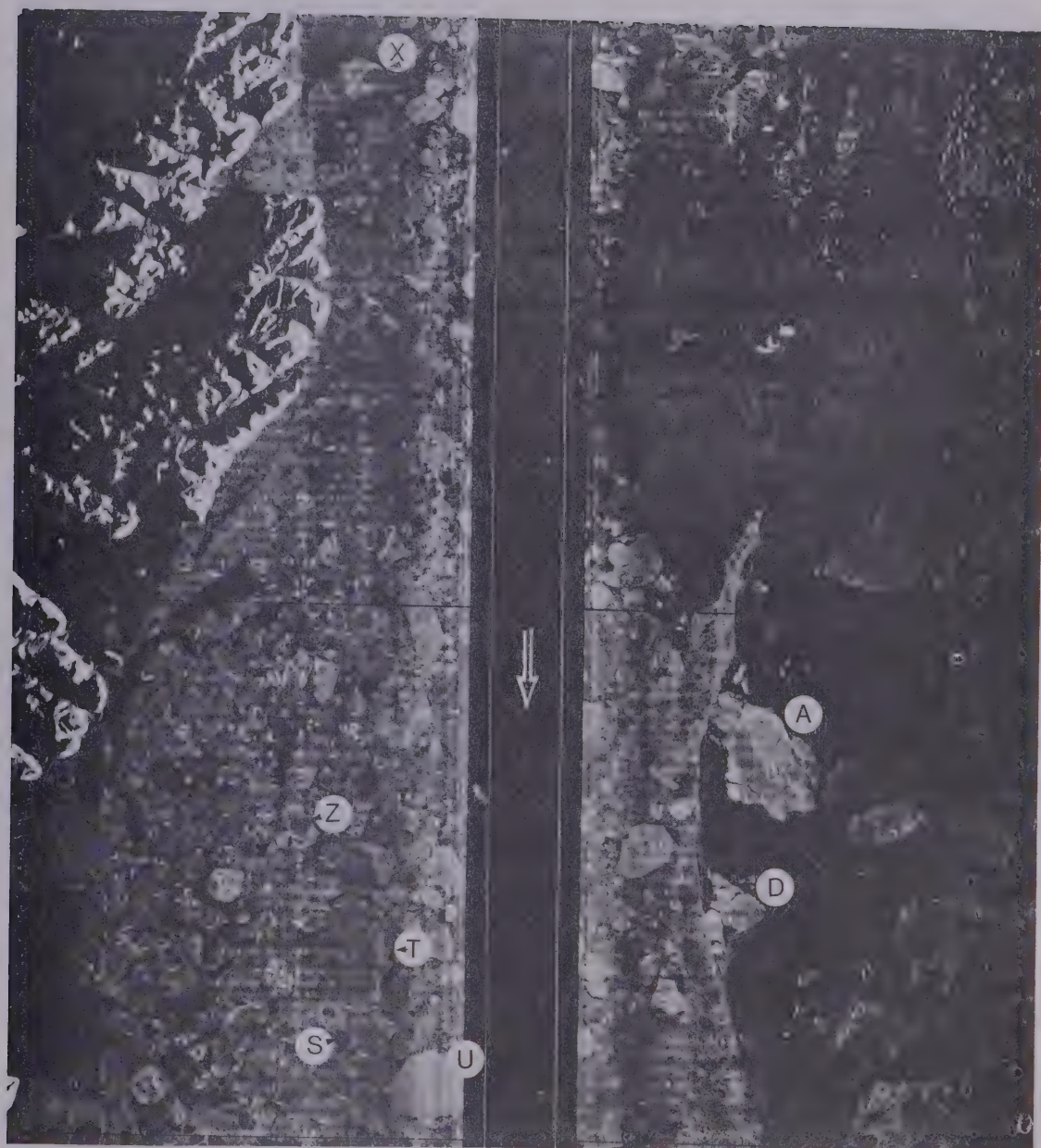


FIG. 5. The same area southbound and at a different scale, 26 October.  
Alt. 1830 m (6000 ft), range 50 km, APS-94D mode (see p.5, 10, 13).



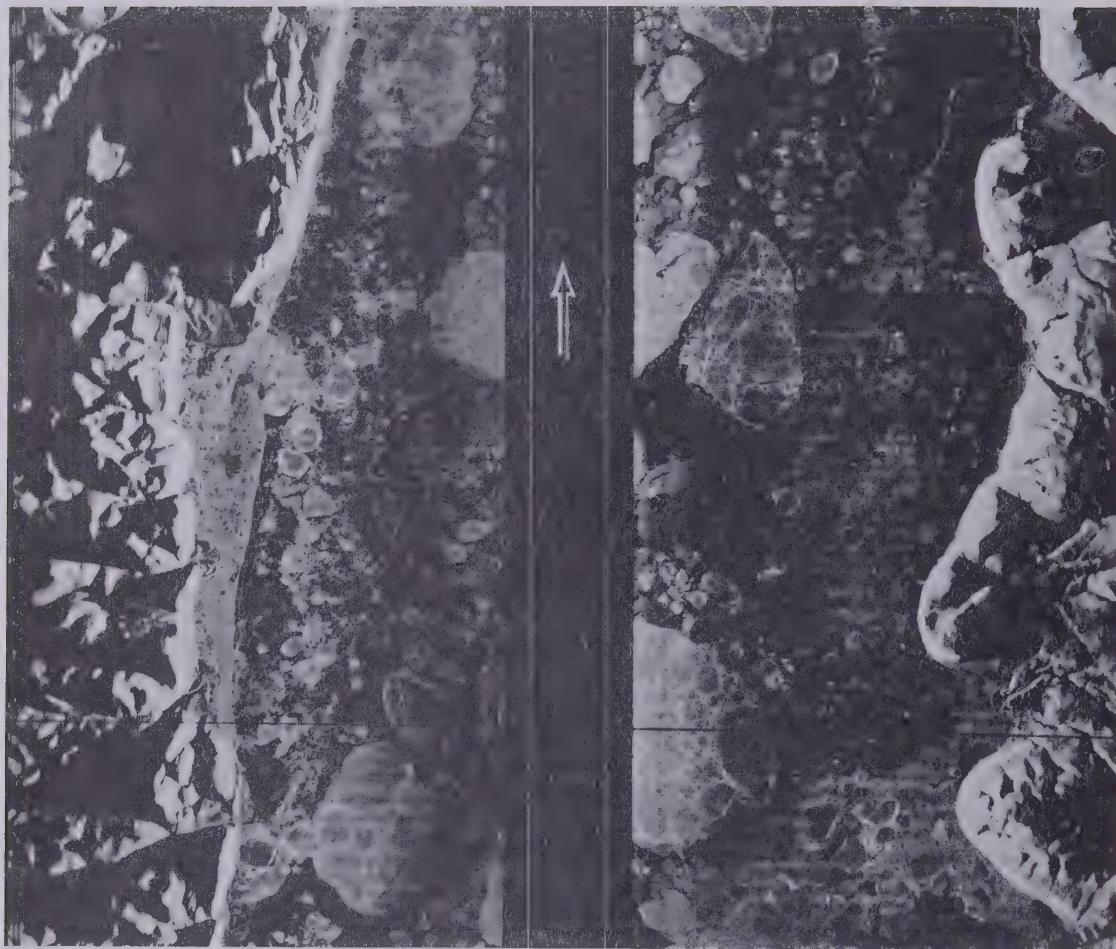


FIG. 6. Northern Kennedy Channel, 26 October, northbound. Note clear-cut edge of fast ice on left. Alt. 915 m (3000 ft) range 25 km, APS-94D mode (see p.4).

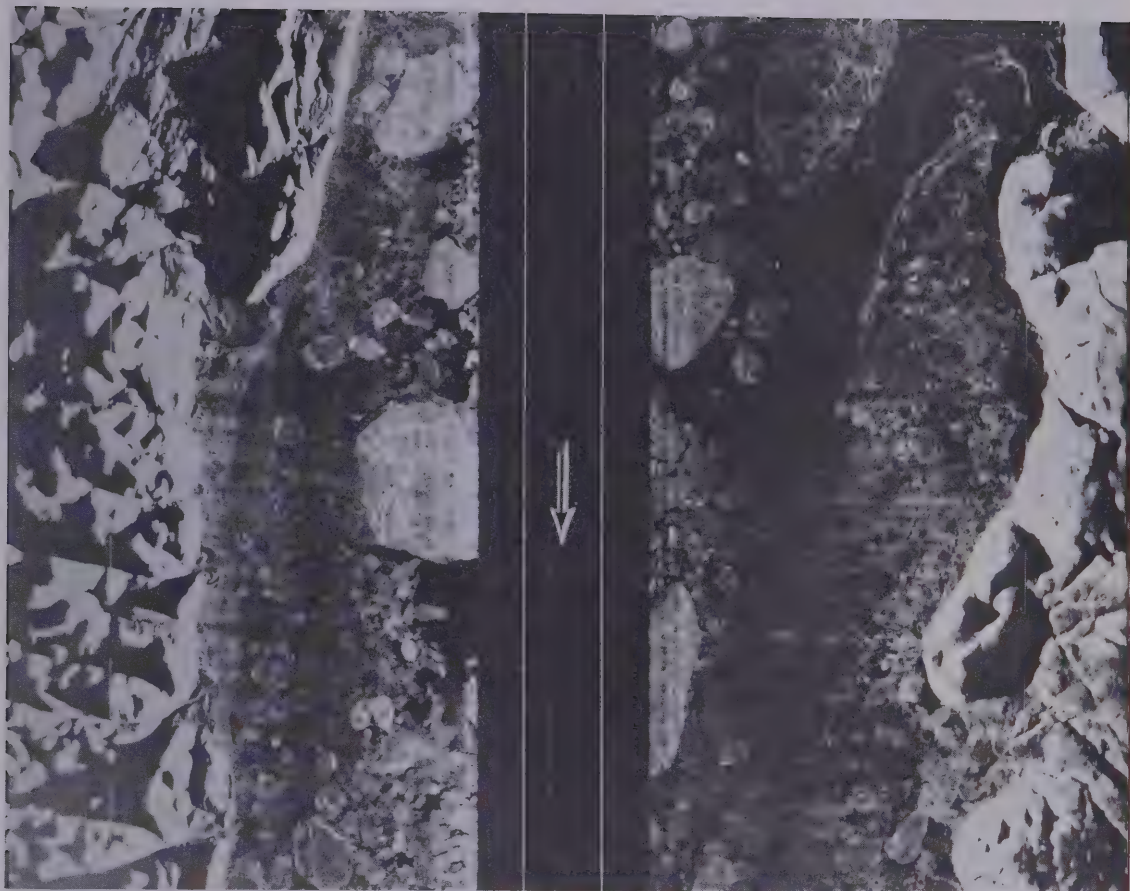


FIG. 7. The same area southbound, 26 October. The fast ice edge here is quite indistinct. Alt. 1830 m (6000 ft), range 25 km, APS-94D mode (see p.4).



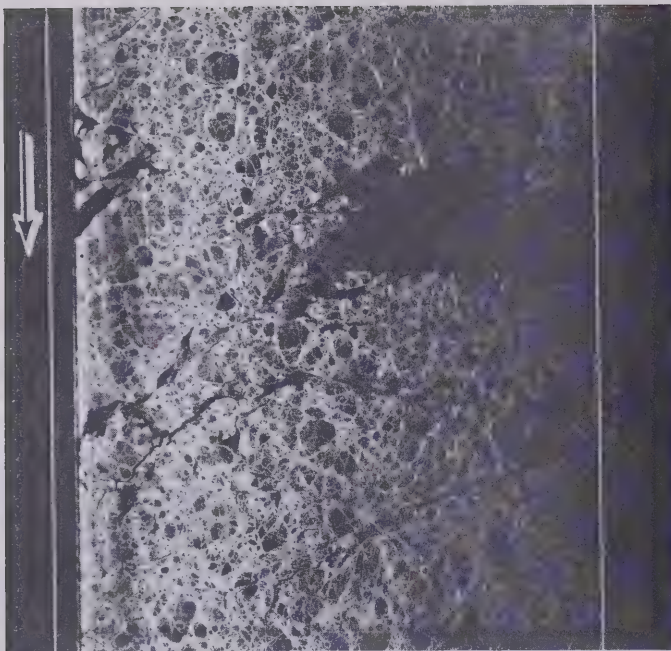


FIG. 8. *The Arctic Ocean at 83°11N, 61°56W on 19 October. Alt. 1220 m (4000 ft), range 50 km, DBS mode. (see p.5, 9).*

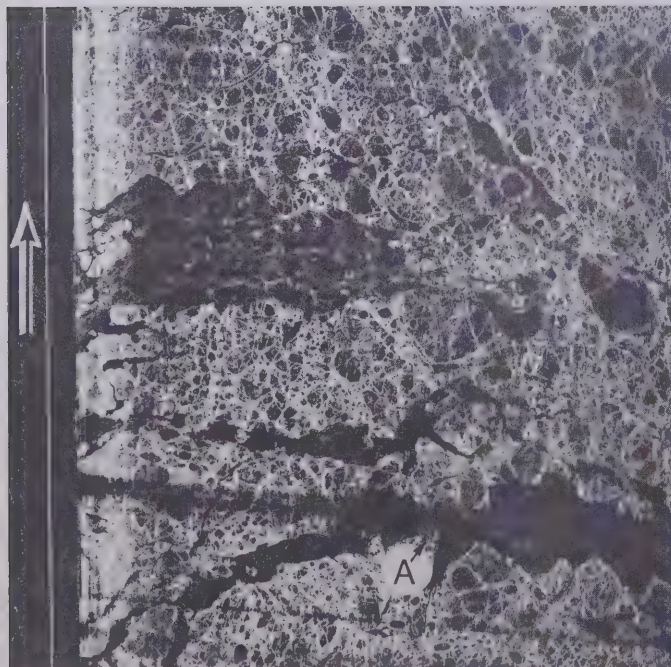


FIG. 9. *The same area on 21 October, showing widening of existing cracks and formation of new ones. Alt. 1220 m (4000 ft), range 50 km, DBS mode (see p.5, 9).*



FIG. 10. The same area on 26 October. More movement and some refreezing can be identified. Alt. 1070 m (3500 ft) range 25 km, APS-94D mode (see p. 5, 9).

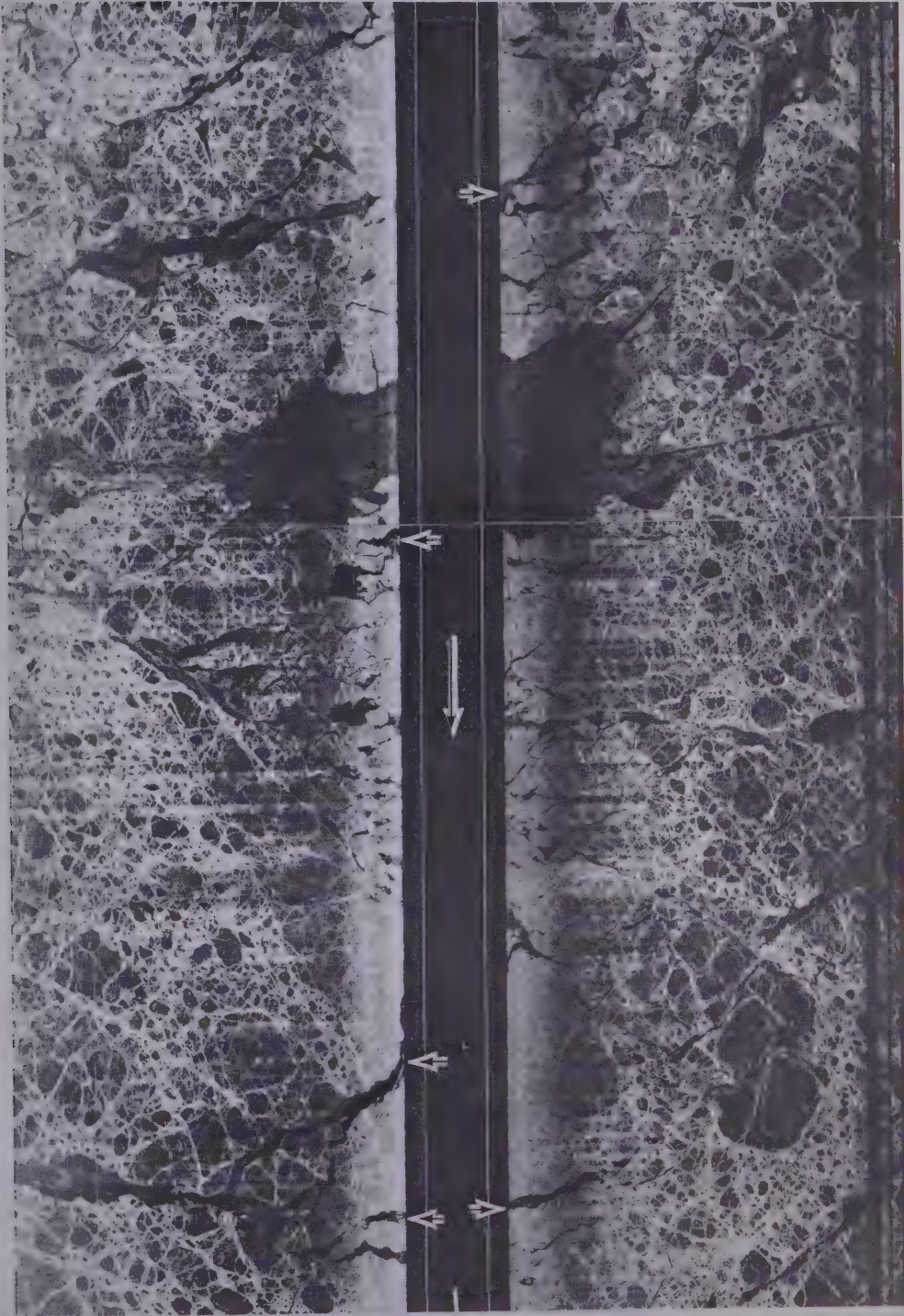
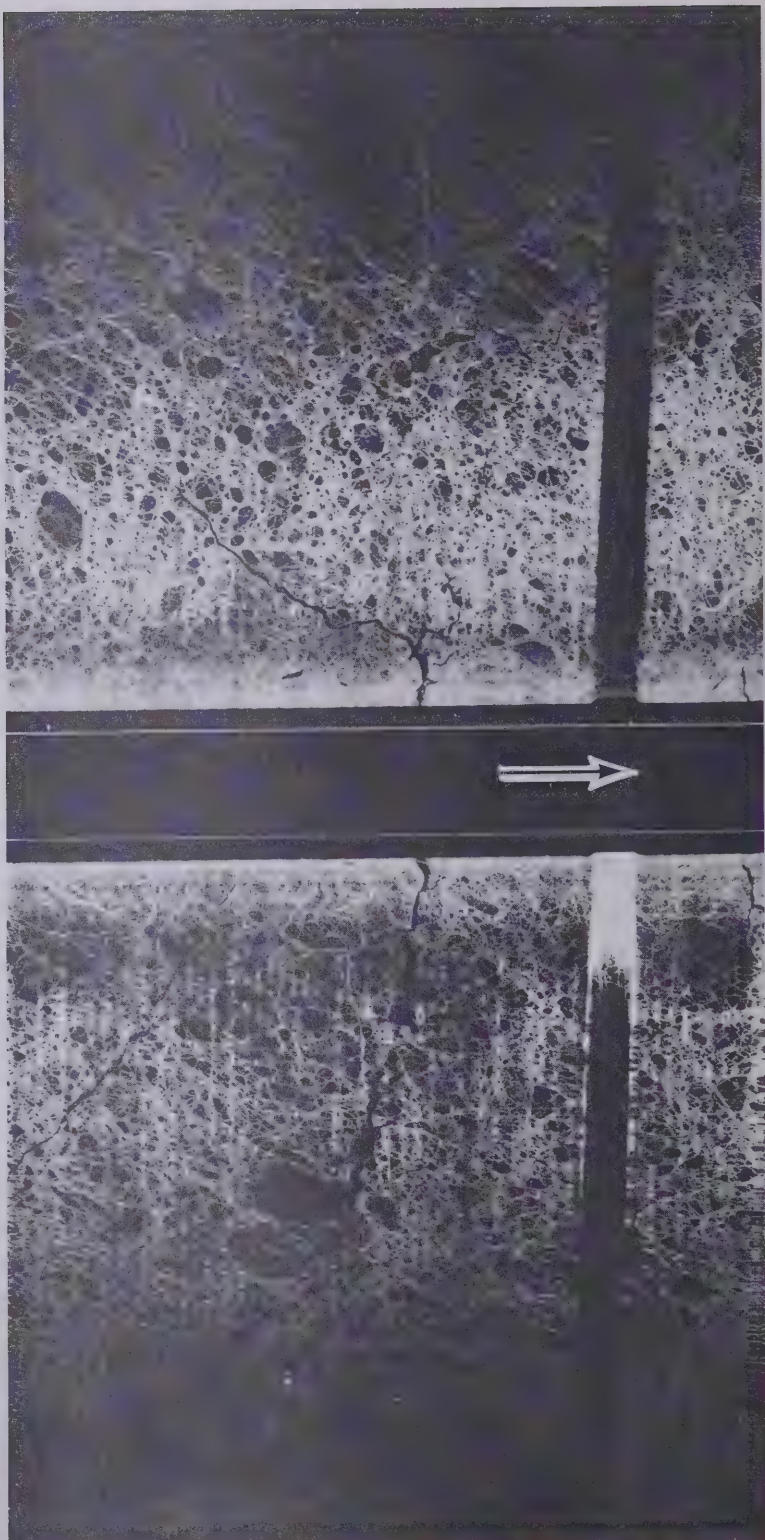
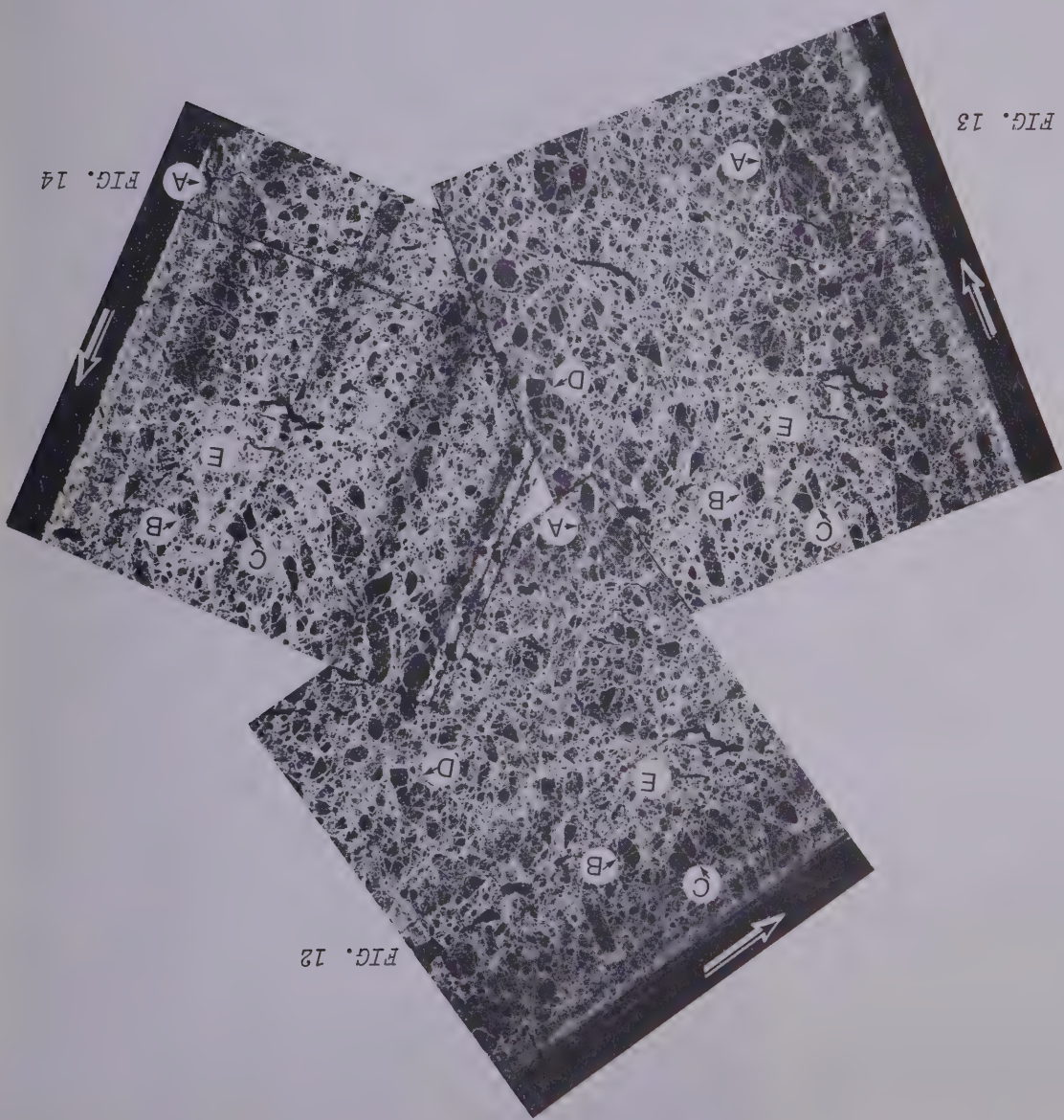


FIG. 11. The Arctic Ocean at  $85^{\circ}00'N$ ,  $70^{\circ}00'W$  on 26 October. The transverse break in the image is caused by a heading alteration. Alt. 1220 m (4000 ft), range 50 km, AFS-94D mode (see p. 5).







FIGS. 12-14.

Three samples from a pattern flown round the rendezvous site, 21 October. The letter E marks the polynga where the submersible surfaced. Alt. 1220 m (4000 ft), range 25 km, DBS mode (see p. 5, 6, 8).

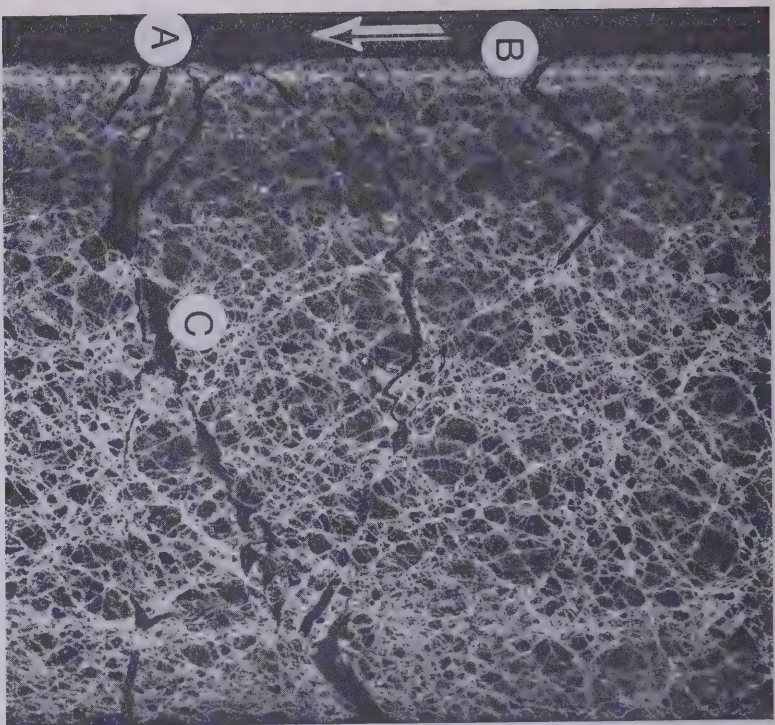


FIG. 15. The Arctic Ocean, about  $85^{\circ}30'N$ ,  $70^{\circ}00'W$ , on 19 October. Northbound, looking west.

Alt. 1220 m (4,000 ft), range 25 km, DBS mode (see p.6, 9).

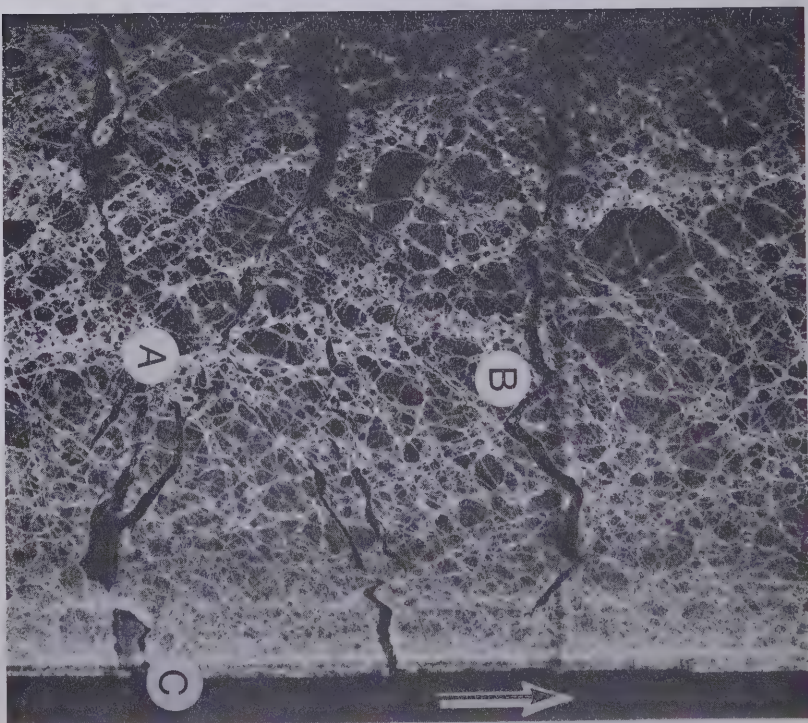


FIG. 16. The same area 30 minutes later on an overlapping track southbound, looking east.



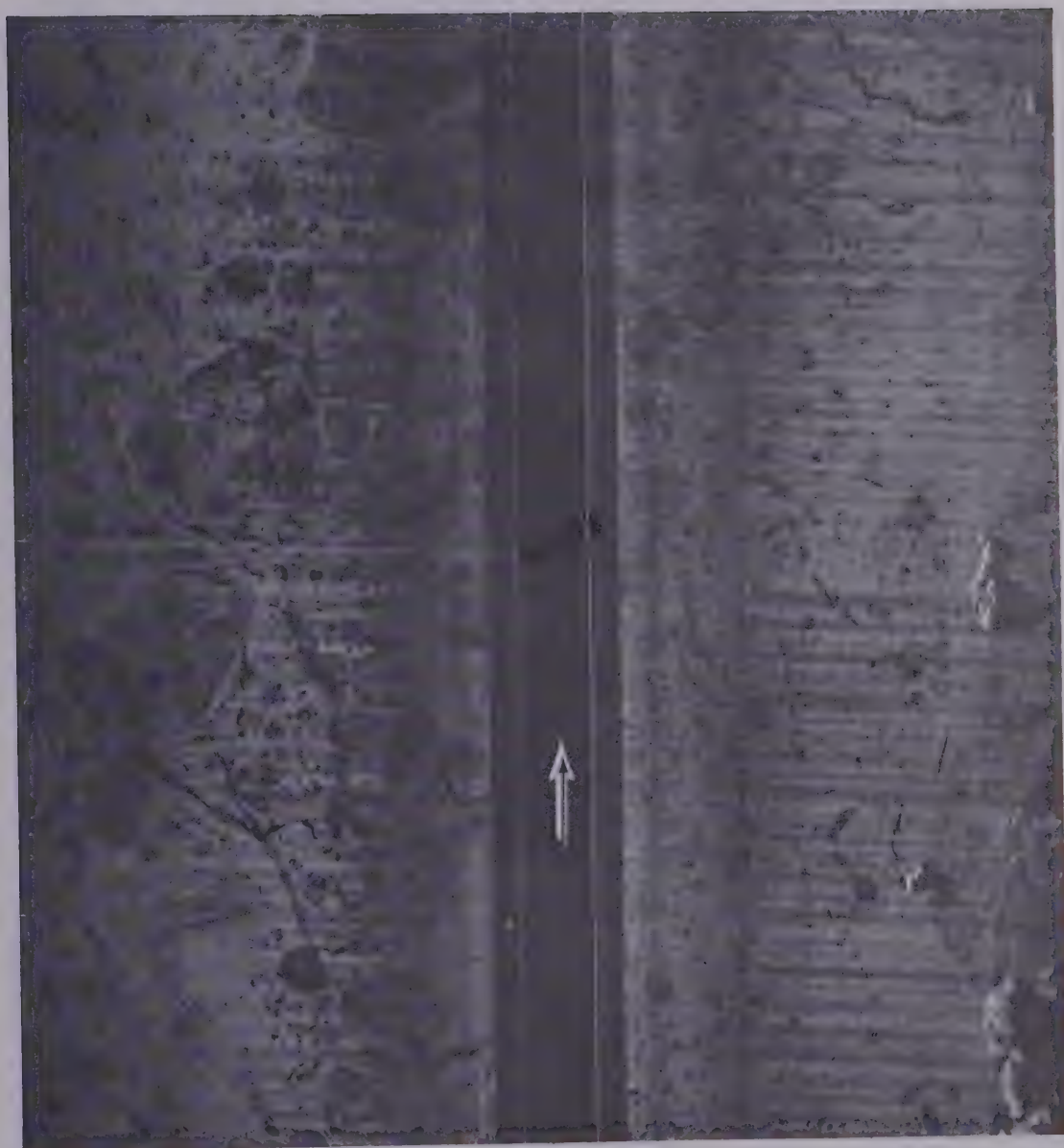


FIG. 17. Part of Hudson Strait, 14 March 1975, showing first-year pack ice. Alt. 1100 m (3600 ft), range 25 km, APS-94D mode (see p.7).

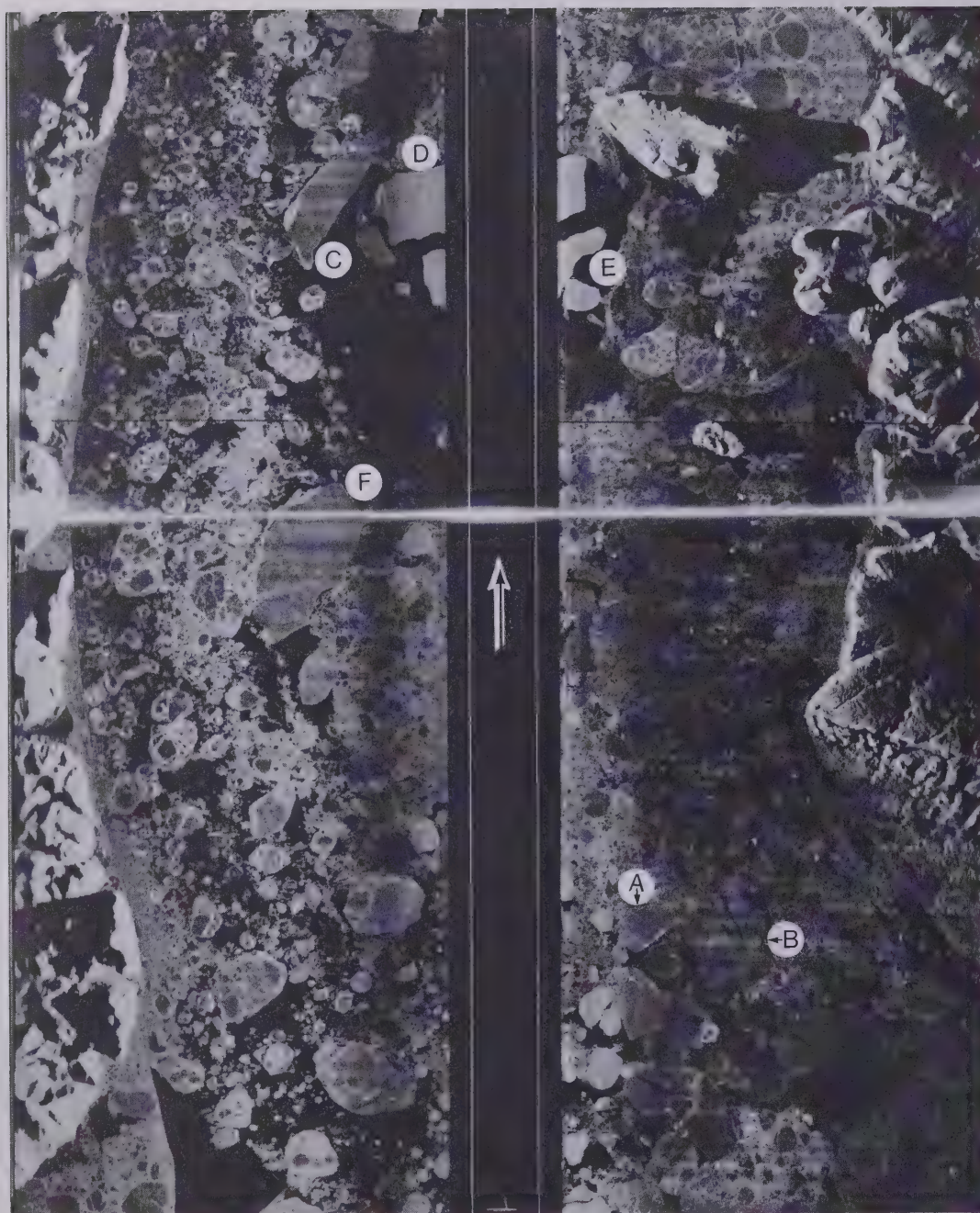


FIG. 18. South part of Kennedy Channel northbound, 26 October. Alt. 915 m (3000 ft), range 25 km, APS-94D mode (see p.6).





FIG. 19. The same area southbound, 26 October. Alt. 1830 m (6000 ft), range 25 km, APS-94D mode (see p.6).

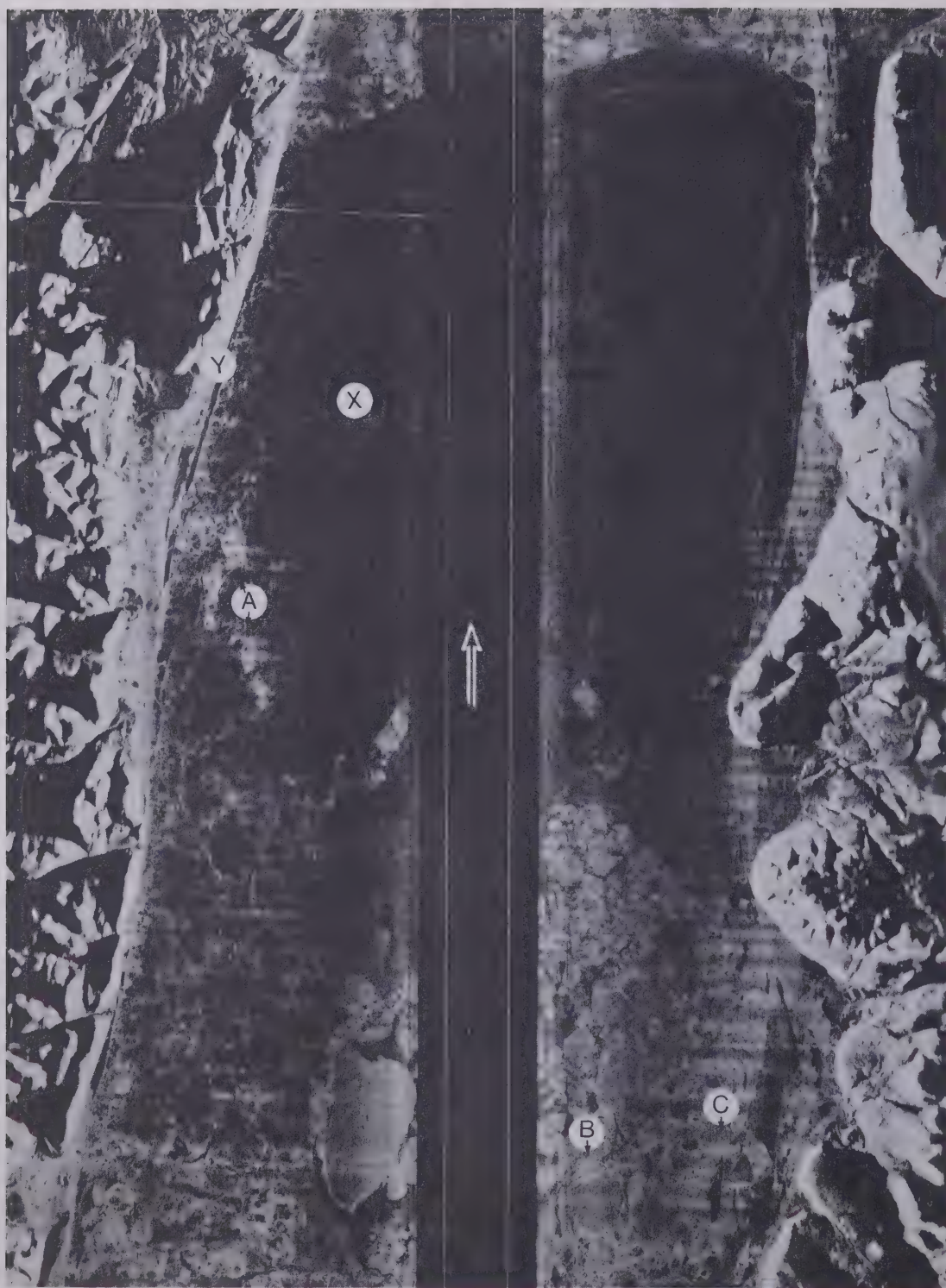


FIG. 20. Kennedy Channel, 13 March 1975, showing smooth first-year ice in the north part and rough consolidated pack ice to the south. Alt. 1220 m (4000 ft), range 25 km, APS-94D mode (see p.7).





FIG. 21. Point X on Fig. 20, 20 May 1975, showing smooth surface. The only relief consisted of 5-cm snowdrifts (see p.7).



FIG. 22. Point Y on Fig. 20, 20 May 1975, showing aircraft tracks in drifted snow disappearing on bare ice. Note the very rough ice in the background (see p.8).

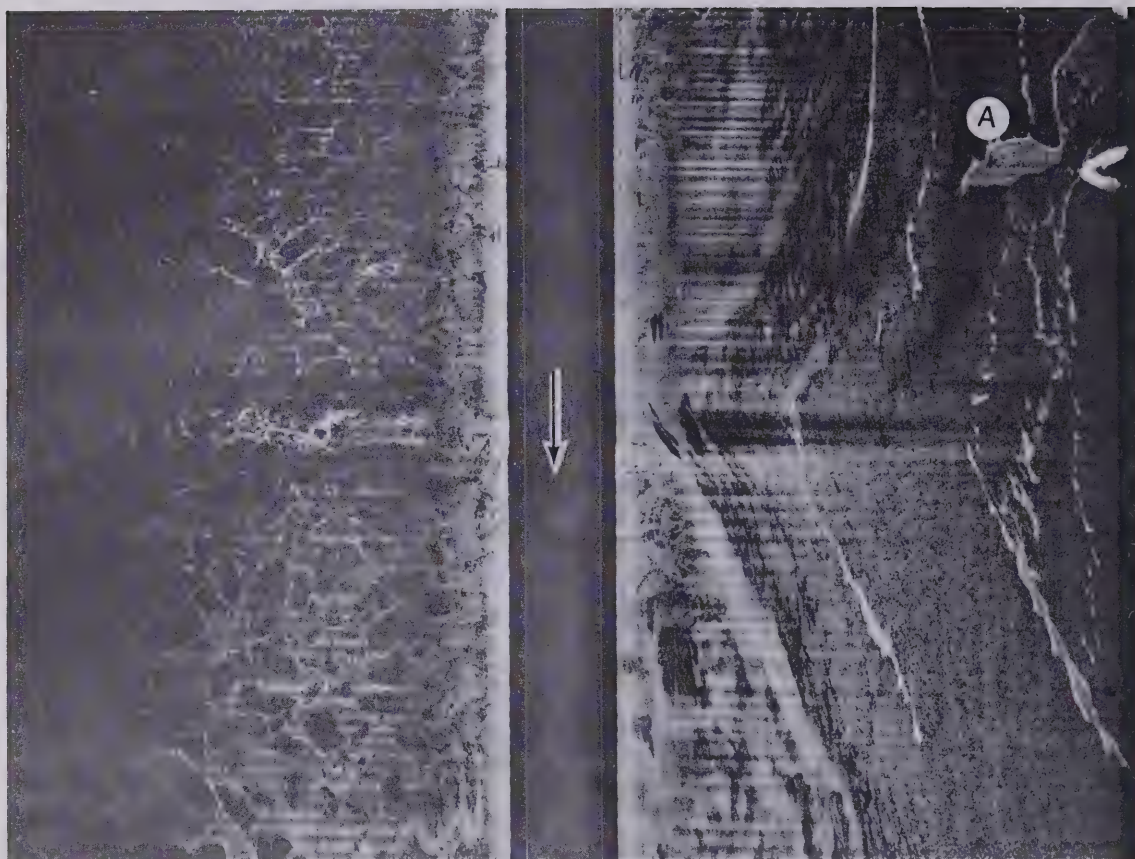


FIG. 23. *Young ice forms in Smith Sound on 13 January 1973. Alt. 915 m (3000 ft), range 25 km, APS-94D mode (see p.8, 9).*

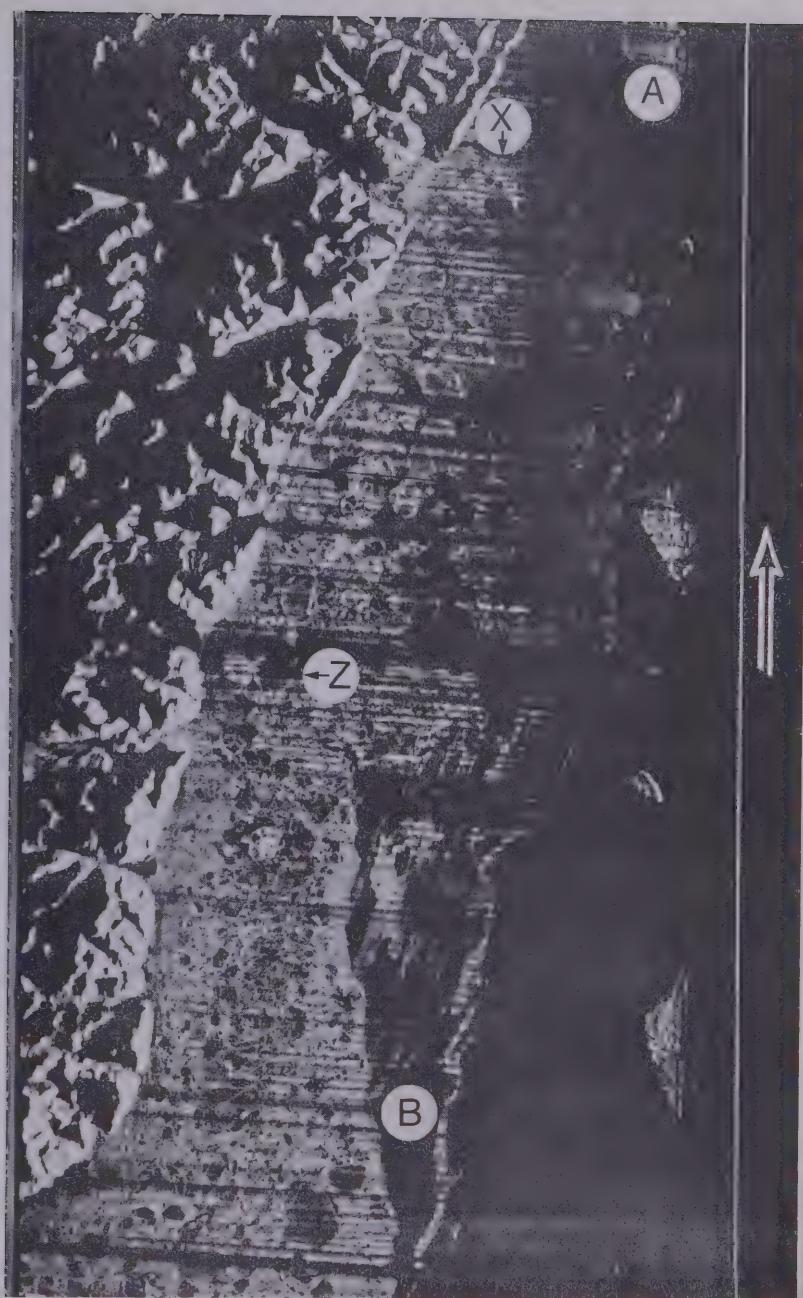


FIG. 24. The west side of Kennedy Channel, 21 October. The many transverse breaks in the image are caused by aircraft motion. Alt. 2440 m (8000 ft), range 50 km, DBS mode (see p.9, 11, 13).



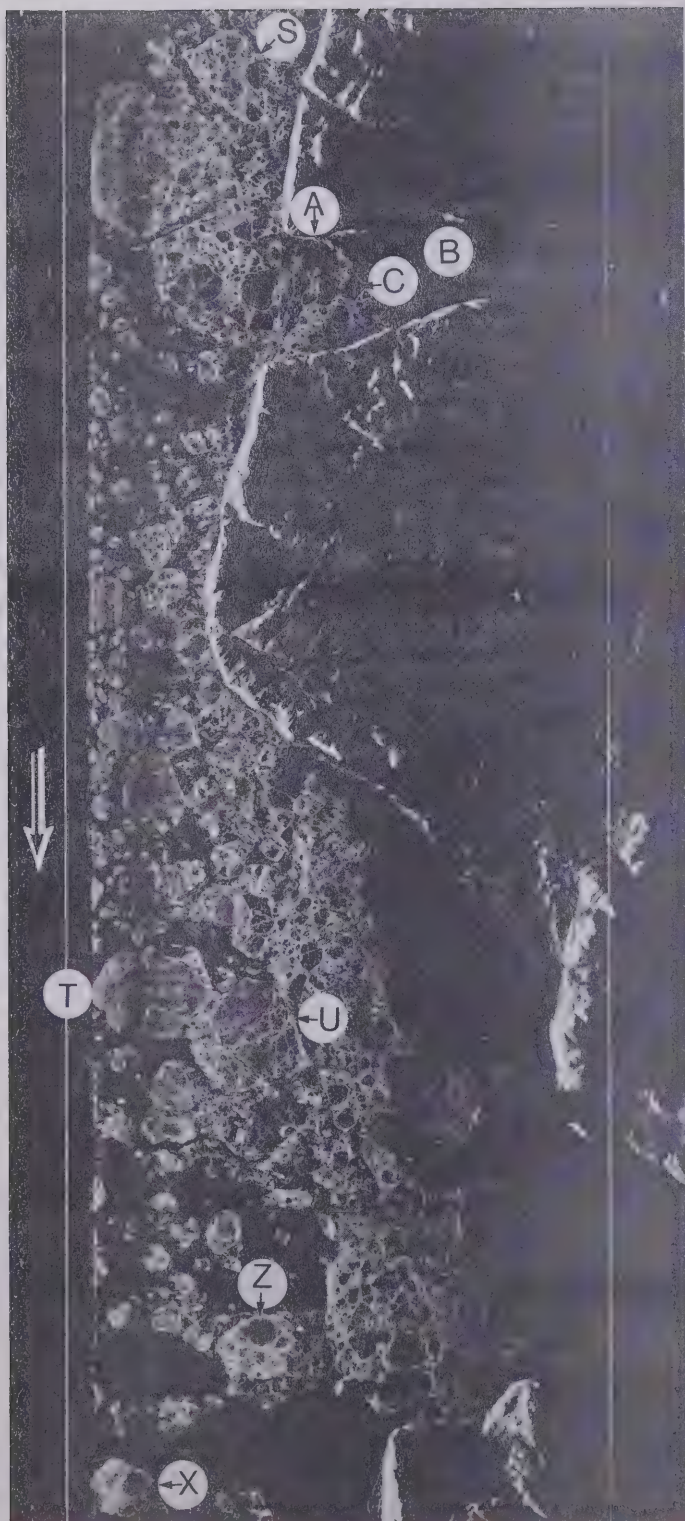


FIG. 25. The east side of Robeson Channel and Hall Basin, 19 October, Newman Bay near the top. Alt. 1220 m (4000 ft), range 50 km, DBS mode (see p.10, 13).

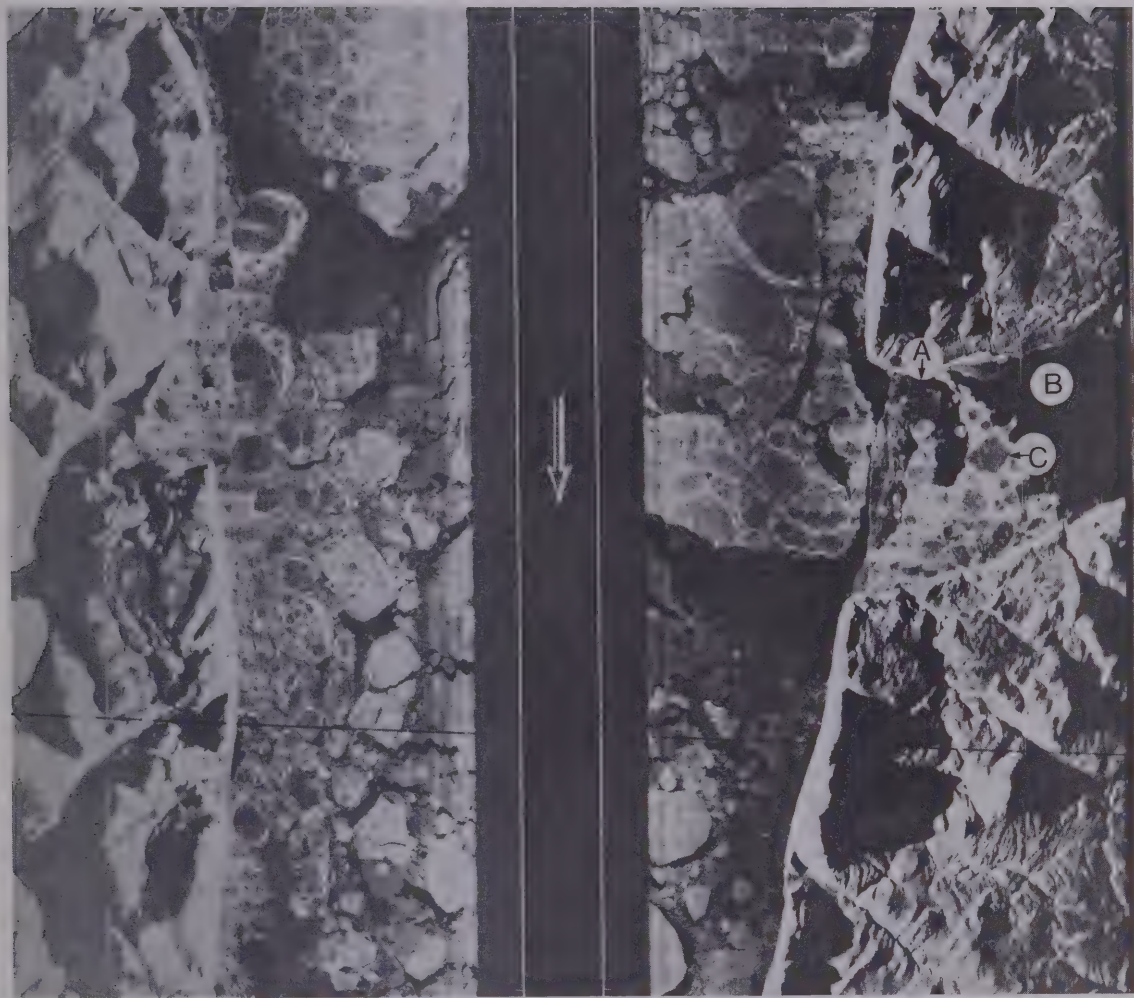


FIG. 26. Robeson Channel, 26 October. Alt. 1830 m (6000 ft), range 25 km, APS-94D mode (see p.10).



FIG. 27. Map of Nares Strait, showing positions of floes S, T, U, X and Z on 19, 21 and 26 October. Only X and Z were identified on the 21 October imagery.



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## KEY WORDS

Ice observations  
 Sea Ice  
 Nares Strait  
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